

## Non-Wood Fiber Utilization in Indian Papermaking: Agro-Residue Potential, Bagasse and Wheat Straw Adoption, and Strategic Alternatives to Wood Pulp Dependency

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**ABSTRACT:** India's paper industry operates under a persistent structural constraint: demand for pulpable wood is approximately 11 million tonnes per annum, while domestic availability is about 9 million tonnes, resulting in a sustained fiber deficit. In this context, non-wood agricultural residues including bagasse, wheat straw, rice straw, and bamboo represent strategically important alternative fiber sources. India generates nearly 500 million tonnes of crop residues annually, of which an estimated 234 million tonnes constitute surplus biomass potentially available for industrial use. Sugarcane processing produces roughly 100 million tonnes of wet bagasse each year, while surplus wheat and rice straw contribute approximately 25 million and 44 million tonnes, respectively. Despite this substantial resource base, agro-residues account for only 6 to 9 percent of total fiber input in Indian papermaking, compared to 73 to 76 percent from recovered fiber and 18 to 21 percent from wood and bamboo. This limited adoption reflects structural constraints including seasonal availability, storage challenges, high silica content in cereal straws, feedstock variability, and competition from energy and fodder applications. Technically, non-wood fibers exhibit shorter fiber length and distinct chemical composition relative to wood, requiring adapted pulping chemistry and recovery systems. However, commercial operations demonstrate that acceptable quality writing, printing, and selected packaging grades can be produced when processing parameters are optimized. This review evaluates agro-residue availability, current utilization patterns, technical characteristics, economic trade-offs, environmental considerations, and policy frameworks influencing non-wood fiber integration. It argues that while non-wood fibers cannot replace recovered paper or wood entirely, they represent a viable and underutilized component of India's long-term fiber security strategy, provided that logistical, technological, and economic barriers are systematically addressed.

**KEYWORDS:** non-wood fibers, agricultural residues, bagasse pulping, wheat straw, rice straw, bamboo, silica management, fiber security, indian paper industry.

### 1 INTRODUCTION

India's paper industry is undergoing sustained expansion driven by rising literacy rates, growth in packaging demand, e-commerce penetration, and increasing consumption of hygiene and specialty paper products. Industry assessments indicate steady growth in production capacity and domestic consumption over the past decade, with further expansion projected in the medium term [1,2]. This growth trajectory intensifies pressure on the sector's primary raw material base, particularly pulpable wood.

The structural fiber challenge facing India's paper industry is well established. Demand for pulpable wood is estimated at approximately 11 million tonnes per annum, while domestic availability is around 9 million tonnes, resulting in a persistent deficit of nearly 2 million tonnes [1]. This shortfall is structural rather than cyclical, arising from limited forest resources, competing land-use priorities, and regulatory constraints on natural forest harvesting. The gap has been managed through imports of wood pulp, increasing utilization of recovered paper, and partial substitution with non-wood agricultural residues [1,2].

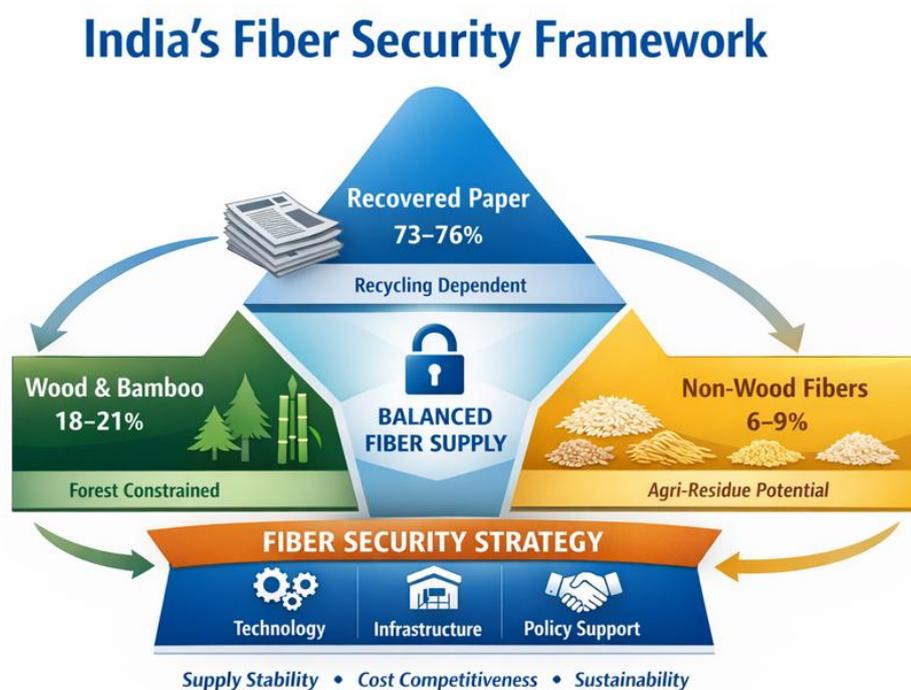
Recovered paper has become the dominant fiber source, accounting for approximately 73 to 76 percent of total fiber input in 2024–25 [1]. Wood and bamboo contribute around 18 to 21 percent, while agro-residues such as bagasse, wheat straw, and rice straw account for only 6 to 9 percent of total furnish [1,2]. This distribution reflects the economic competitiveness and established collection infrastructure associated with recycled fiber. However, reliance on recovered fiber also exposes the industry to volatility in global waste paper markets and import dependencies, particularly during periods of supply disruption [2].

International experience demonstrates that non-wood fibers can play a significant role in national pulp and paper sectors, especially in regions with limited forest resources. FAO production statistics indicate that agricultural residues and bamboo contribute meaningfully to fiber supply in several Asian countries with constrained forestry bases [3]. Historically, non-wood materials such as bagasse and straw have been successfully pulped using adapted chemical processes, and their morphological and chemical characteristics are well documented in established pulping literature [4,5]. These precedents indicate that non-wood fiber utilization is technically established rather than experimental, provided that appropriate process configurations are adopted.

In the Indian context, large volumes of agricultural residues are generated annually, including sugarcane bagasse, wheat straw, and rice straw [6]. Despite this substantial theoretical resource base, their contribution to total fiber input remains modest. The limited share reflects structural constraints including seasonal availability, elevated silica content in cereal straws, feedstock variability, storage challenges, and competition from alternative applications such as biomass energy and fodder [7].

Given projected sectoral growth and the structural nature of the fiber deficit, diversification of raw material sources is strategically important. Non-wood fibers cannot replace recovered paper or wood entirely, but they may function as a complementary pillar within a broader fiber security framework. A systematic assessment of availability, technical feasibility, economic viability, and policy support mechanisms is therefore warranted.

This review examines the scale, composition, and utilization of non-wood fibers in Indian papermaking. It analyzes agro-residue availability, technical characteristics of major feedstocks, economic and environmental considerations, and structural constraints limiting wider adoption. The structural configuration of India's fiber supply can be conceptualized as a three-pillar framework comprising recovered paper, wood and bamboo, and non-wood agricultural residues. Their relative contributions and strategic interdependence are illustrated in Figure 1.



**Fig. 1.** India's Fiber Security Framework

As shown in Figure 1, recovered paper currently forms the dominant pillar of India's fiber base, while wood and bamboo provide structural stability within resource constraints. Non-wood fibers, though presently limited in share, represent a strategically expandable component. The balance among these three streams determines long-term fiber security.

## 2 METHODOLOGY AND DATA SOURCES

This review is based on structured secondary data analysis of institutional statistics, government publications, technical monographs, peer-reviewed journal articles, and industry reports.

Agricultural residue generation data were derived primarily from official agricultural statistics and national biomass assessments published by the Ministry of Agriculture and the Ministry of New and Renewable Energy (MNRE) [6,8]. These sources provide crop

production volumes, residue-to-product ratios, and estimates of surplus biomass after accounting for fodder use, domestic fuel consumption, and soil incorporation requirements.

Paper industry fiber consumption data, including the relative shares of recovered paper, wood and bamboo, and agro-residues, were obtained from performance reports of the Indian Paper Manufacturers Association (IPMA) and sectoral assessments published by the India Brand Equity Foundation (IBEF) [1,2]. Where necessary, industry-level economic and structural insights were supplemented using sectoral market analyses [9].

Technical characteristics of non-wood fibers, including fiber morphology, lignin content, silica levels, and pulping behavior, were referenced from established pulping literature and non-wood fiber handbooks [4,5]. Additional contextual information on biomass utilization pathways and competing energy applications was drawn from renewable energy and biomass resource studies [7].

International comparative data were referenced from FAO production and forestry statistics to situate India’s non-wood fiber utilization within a broader global context [3].

Where multiple estimates existed for residue generation or fiber share, the analysis prioritized consistency across authoritative sources rather than relying on isolated point estimates. Reported values are presented as published in the respective source documents, without adjustment for inflation or currency conversion. Variations in methodological assumptions—particularly in the definition of “surplus biomass” and the accounting of competing applications—are acknowledged as inherent limitations of secondary data synthesis.

This review does not involve primary data collection or experimental validation. Instead, it integrates available statistical and technical evidence to provide a structured assessment of non-wood fiber potential within India’s pulp and paper sector.

### 3 AGRO-RESIDUE AVAILABILITY IN INDIA

#### 3.1 TOTAL CROP RESIDUE GENERATION

India generates one of the world’s largest agricultural residue streams due to its extensive cereal and sugarcane production. Total crop residue generation is estimated at approximately 500 million tonnes annually, based on crop output and residue-to-product ratios reported in national agricultural statistics and supported by peer-reviewed biomass assessments [6,10]. Of this total, roughly 234 million tonnes are categorized as surplus biomass potentially available for non-agricultural applications after accounting for fodder use, domestic fuel consumption, and soil incorporation requirements [8]. The major categories of agricultural residues relevant to papermaking and their estimated annual availability are summarized in Table 1.

*Table 1. Estimated Agricultural Residue Availability in India*

Residue Type	Estimated Annual Generation (Million Tonnes)	Surplus Available for Industrial Use (Million Tonnes)	Key Producing Regions
Sugarcane Bagasse	~100 (wet)	~45–50 (dry basis equivalent)	Maharashtra, UP, Karnataka, Tamil Nadu
Wheat Straw	~110–120	~25	Punjab, Haryana, Uttar Pradesh
Rice Straw	~140–150	~44	Punjab, Haryana, West Bengal
Total Crop Residue (All Crops)	~500	~234	Pan-India

*Note: Surplus estimates exclude fodder, domestic fuel, and soil incorporation requirements.*

The magnitude of this resource base positions India among the few countries where agricultural residues could meaningfully supplement industrial fiber supply. However, residue availability is regionally concentrated and crop-specific. Northern states such as Punjab, Haryana, and Uttar Pradesh account for significant shares of wheat and rice residues, while Maharashtra, Uttar Pradesh, and Karnataka contribute substantially through sugarcane cultivation [6]. This regional clustering has direct implications for collection logistics, transportation costs, and the feasibility of locating non-wood-based pulp and paper facilities near residue generation centers.

Variability in residue availability also arises from climatic conditions, cropping intensity, and competing agricultural uses. Therefore, theoretical surplus does not automatically translate into economically recoverable fiber supply, and practical availability depends on local collection infrastructure and price competitiveness relative to alternative applications [8].

### 3.2 BAGASSE FROM SUGARCANE

Sugarcane bagasse represents the most commercially established non-wood fiber source in Indian papermaking. India is the world's second-largest sugarcane producer after Brazil, with annual production typically ranging between 350 and 400 million tonnes according to FAO and national agricultural statistics [3,6]. Processing of this volume yields approximately 28 to 30 percent bagasse by weight, translating to nearly 100 million tonnes of wet bagasse annually, or roughly 45 to 50 million tonnes on a dry basis, consistent with established non-wood fiber conversion ratios reported in technical literature [6,11].

Bagasse offers structural advantages as a papermaking raw material. Unlike cereal straw, it is generated in concentrated volumes at sugar mills, significantly reducing primary collection complexity. The sugarcane crushing season extends over six to eight months in many regions, providing relatively predictable seasonal supply. Additionally, the fiber morphology and chemical composition of bagasse have been extensively documented in pulping literature, and established soda and soda–anthraquinone pulping processes are commercially proven for this feedstock [4,11].

Several Indian mills operate integrated sugar–paper complexes to utilize captive bagasse. Tamil Nadu Newsprint and Papers Limited (TNPL) has consistently reported substantial bagasse utilization in its annual disclosures, demonstrating commercial-scale viability for writing and printing grades [12]. Such integration reduces raw material procurement risk and partially insulates mills from fluctuations in global pulp markets.

However, bagasse also competes with cogeneration applications within sugar mills, where it is used for steam and electricity generation. The allocation between energy use and fiber use depends on power tariffs, energy demand, and the relative economics of pulp production versus electricity sales [8].

### 3.3 WHEAT AND RICE STRAW

Wheat and rice straw collectively represent the second-largest category of agricultural residue available for industrial utilization in India. Wheat cultivation generates an estimated 25 million tonnes of surplus straw annually after meeting fodder and traditional rural uses, while rice straw contributes approximately 44 million tonnes of surplus biomass [6,8].

Unlike bagasse, which is generated at centralized industrial processing points, cereal straw is produced across dispersed agricultural holdings. This spatial dispersion increases collection, aggregation, and transportation costs. In northern India, particularly Punjab and Haryana, large-scale residue generation has led to the recurring practice of stubble burning, contributing to severe seasonal air pollution episodes [16]. The scale of this issue underscores both the magnitude of available straw and the limited development of economically attractive utilization pathways.

Several paper mills in northern India have developed structured procurement systems for wheat straw. These typically involve contracts with farmers or intermediaries, organized baling operations, and mechanical preprocessing steps such as depithing to reduce silica-rich fractions prior to pulping. Technical literature indicates that cereal straw pulping requires adapted chemical recovery strategies due to elevated silica content compared with wood-based systems [5]. When blended with recovered fiber or wood pulp, wheat straw can be used for writing, printing, and certain packaging grades, although furnish optimization is necessary to maintain strength properties and drainage performance [4,5].

Despite demonstrated technical feasibility, large-scale expansion of straw-based pulping remains constrained by silica management challenges, seasonal availability, feedstock variability, and competition from alternative agricultural uses.

### 3.4 BAMBOO RESOURCES

Bamboo occupies an intermediate position between wood and agricultural residues in India's non-wood fiber landscape. Botanically a perennial grass, bamboo exhibits fiber characteristics closer to hardwood, including relatively longer fiber length compared with cereal straw and bagasse [5]. These characteristics make bamboo suitable for a broader range of paper grades, including packaging and specialty applications where fiber length contributes to improved tear strength and sheet integrity.

India possesses significant bamboo resources, particularly in northeastern states such as Assam, Arunachal Pradesh, and Tripura. FAO forestry statistics estimate India's bamboo-bearing area at approximately 13 to 15 million hectares, making it one of the largest bamboo resource bases globally [3]. Historically, bamboo served as a principal raw material for several Indian pulp mills prior to the expansion of plantation forestry and increased reliance on recovered paper.

However, bamboo procurement presents structural challenges distinct from annual crop residues. Harvesting is labor-intensive and often conducted in remote forested regions with limited transport infrastructure. Bamboo culms also compete with construction, handicraft, and emerging biomass energy applications. In addition, sustainable harvesting requires adherence to regeneration cycles and forest management regulations to prevent resource depletion, introducing ecological and administrative constraints.

Consequently, while bamboo remains regionally significant and technically suitable for pulp production, its role as a large-scale substitute for wood fiber is constrained by logistical, regulatory, and sustainability considerations.

#### 4 CURRENT NON-WOOD FIBER UTILIZATION IN INDIAN PAPER PRODUCTION

##### 4.1 OVERALL FIBER MIX

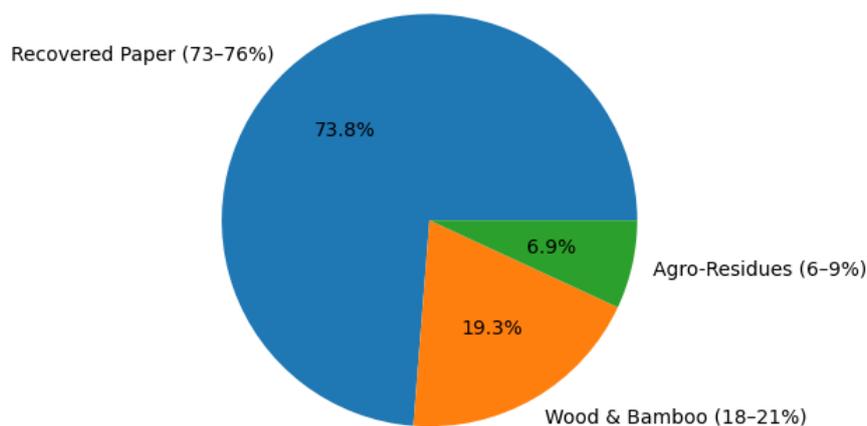
As of 2024–25, India’s paper industry operates on a fiber mix dominated by recovered paper at approximately 73 to 76 percent of total furnish, while wood and bamboo contribute around 18 to 21 percent and agro-residues account for only 6 to 9 percent [1]. These proportions are reported in industry performance assessments and reflect the structural orientation of the sector toward recycled fiber [1,2]. The current furnish structure of the Indian paper industry is presented in Table 2.

*Table 2. Fiber Mix Composition in Indian Paper Industry (2024–25)*

Fiber Source	Share of Total Fiber Input (%)	Structural Characteristics
Recovered Paper	73–76	Cost competitive, established collection network
Wood & Bamboo	18–21	Stable quality, limited domestic availability
Agro-Residues	6–9	Seasonal, silica constraints, logistics intensive

The proportional dominance of recovered paper within the national furnish structure is illustrated in Figure 2.

Fiber Mix Distribution in Indian Paper Industry (2024–25)



*Fig. 2. Fiber mix distribution in the Indian paper industry (2024–25)*

The dominance of recovered paper is primarily explained by established domestic collection systems, import channels for waste paper, and relatively mature processing infrastructure. Recovered fiber often provides cost advantages compared to virgin wood pulp, particularly during periods of stable international waste paper supply [2]. In contrast, the modest contribution of agro-residues, despite substantial theoretical availability, reflects operational and structural constraints rather than raw material scarcity. These constraints include seasonal generation, silica-related recovery challenges, logistical complexity, and competition from alternative applications, which are examined in subsequent sections.

##### 4.2 BAGASSE-BASED PRODUCTION

Bagasse utilization in Indian papermaking is concentrated in integrated sugar–paper mill complexes located in major sugarcane-producing regions. These facilities are designed to process bagasse as a primary or significant secondary fiber source, thereby ensuring captive raw material supply and reducing exposure to volatile pulp markets. Integration lowers procurement costs and leverages existing infrastructure for storage, handling, and preprocessing.

Tamil Nadu Newsprint and Papers Limited (TNPL) has consistently reported large-scale use of bagasse as part of its furnish mix, demonstrating sustained commercial viability for newsprint and writing and printing grades [12]. Industry assessments further indicate that selected paperboard and printing paper producers incorporate bagasse in defined product segments where furnish optimization permits substitution without compromising performance specifications [2].

Technically, bagasse-based paper production is well established. Pulping literature documents that bagasse fibers are shorter than softwood fibers and therefore require blending with longer-fiber pulps or process adjustments in refining and sheet formation to maintain adequate tear strength and machine runnability [4,5]. Chemical pulping of bagasse is commonly carried out using soda or soda–anthraquinone processes rather than conventional kraft pulping, owing to its comparatively lower lignin content and distinct chemical composition [4,11]. These adapted processes are commercially proven and form the basis of integrated bagasse-based pulp production in India.

However, bagasse also competes with cogeneration applications within sugar mills, where it is used for steam and electricity generation. The allocation between energy and pulp applications is influenced by relative market returns and policy incentives related to biomass-based power generation [8].

### 4.3 WHEAT STRAW MILLS

Wheat straw utilization is geographically concentrated in northern India, particularly in Punjab, Haryana, and western Uttar Pradesh, where wheat cultivation is intensive and mills have developed structured procurement systems. Straw is typically sourced through farmer contracts, aggregators, or dealer networks, with collection occurring immediately after harvest when residue availability is highest [6].

Straw-based pulping presents technical challenges distinct from bagasse operations. Wheat straw contains higher silica levels than wood or bagasse, which complicates chemical recovery in conventional alkali pulping systems and promotes scaling in evaporators and recovery boilers [5]. Silica accumulation increases maintenance requirements and may necessitate partial chemical cycle bleed or mechanical depithing to reduce silica-rich outer fractions prior to pulping [5]. These measures increase operational complexity and cost relative to wood-based systems.

Despite these constraints, wheat straw has been used successfully for writing, printing, and selected packaging grades when appropriately blended with recovered fiber or wood pulp [4]. Technical literature indicates that furnish optimization is critical, as excessive straw content may affect drainage behavior, brightness response, and surface characteristics [4,5]. While straw incorporation can reach significant proportions in specialized mills, product performance requirements generally necessitate balanced blending strategies rather than complete substitution of longer-fiber components.

## 5 TECHNICAL CHARACTERISTICS OF NON-WOOD FIBERS

### 5.1 FIBER MORPHOLOGY

The principal technical distinction between non-wood fibers and conventional wood pulps lies in their morphological characteristics. Fiber length is a primary determinant of paper strength properties, particularly tear resistance and tensile performance. Softwood fibers, which form the strength backbone in many paper grades, typically exhibit average fiber lengths of approximately 3–4 mm. Hardwood fibers are shorter, generally ranging from 1.0 to 1.5 mm. In comparison, bagasse fibers typically range between 1.5 and 2.0 mm, wheat straw fibers between 1.0 and 1.5 mm, and rice straw fibers are often slightly shorter [4,5,11].

These dimensional differences directly influence sheet structure and mechanical behavior. Shorter fibers tend to improve formation and surface smoothness but may reduce tear strength when used without reinforcement from longer fibers. Consequently, non-wood pulps are frequently blended with softwood pulp or optimized through refining adjustments to balance strength and formation characteristics [4].

Beyond fiber length, parameters such as fiber diameter, cell wall thickness, and lumen dimensions differ significantly between wood and non-wood materials. Non-wood fibers often possess thinner cell walls and relatively larger lumen diameters compared to softwood fibers [5]. These structural features can promote fiber collapse during sheet formation, contributing to enhanced inter-fiber bonding and opacity. However, they may also influence drainage behavior during papermaking, requiring adjustments in refining intensity and wet-end chemistry.

These morphological differences should not be interpreted as inherent deficiencies. Rather, they represent material-specific characteristics that necessitate adapted furnish design and process control strategies to achieve targeted product specifications.

**5.2 CHEMICAL COMPOSITION**

In addition to morphological variation, non-wood fibers differ chemically from wood. Lignin content plays a central role in pulping chemistry and chemical demand. Softwood typically contains 25–30 percent lignin, while hardwood contains approximately 20–25 percent. Bagasse generally contains 18–24 percent lignin, with wheat and rice straw exhibiting comparable overall lignin ranges but differing in lignin structure and distribution [4,11].

The relatively lower lignin content of bagasse can reduce delignification severity compared with softwood, enabling soda-based pulping systems to operate effectively. However, cereal straws introduce a distinct chemical challenge in the form of elevated ash and silica content. Rice straw may contain 10–15 percent silica on a dry basis, wheat straw approximately 4–8 percent, while wood typically contains less than 1 percent inorganic material [5].

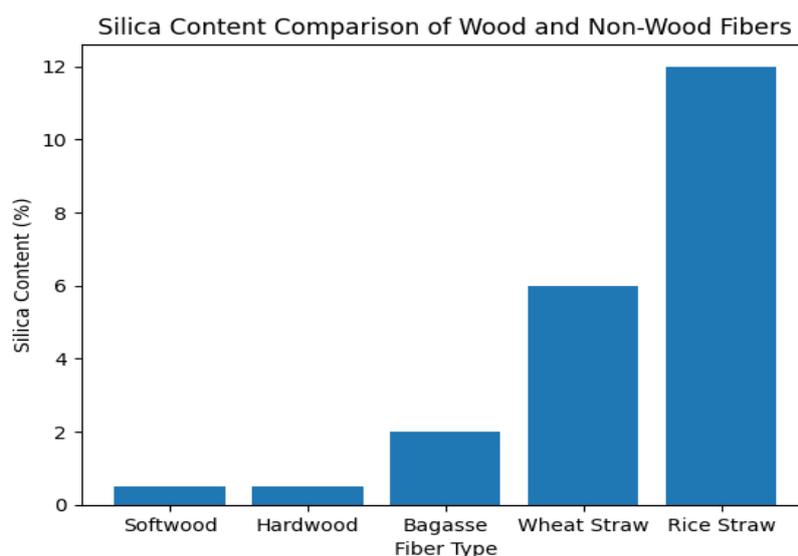
High silica content significantly affects chemical recovery operations. During pulping and recovery, silica does not participate in combustion or chemical regeneration within the alkali cycle. Instead, it can accumulate as deposits on heat transfer surfaces in evaporators and recovery boilers, contributing to scaling, reduced thermal efficiency, and increased maintenance frequency [5]. These effects impose operational constraints that limit the practical proportion of cereal straw in mills equipped with conventional chemical recovery systems.

Hemicellulose composition also differs between non-wood and wood fibers, influencing pulp yield, fiber swelling behavior, and bonding potential. Non-wood fibers generally contain higher proportions of certain hemicellulosic fractions, which can enhance inter-fiber bonding but may also increase alkali consumption during pulping [4]. A comparative overview of key morphological and chemical characteristics of wood and selected non-wood fibers is presented in Table 3.

*Table 3. Technical Comparison of Wood and Non-Wood Fibers*

Parameter	Softwood	Hardwood	Bagasse	Wheat Straw	Rice Straw
Fiber Length (mm)	3–4	1.0–1.5	1.5–2.0	1.0–1.5	<1.5
Lignin Content (%)	25–30	20–25	18–24	15–22	12–20
Silica Content (%)	<1	<1	1–3	4–8	10–15
Typical Pulping Process	Kraft	Kraft	Soda / Soda-AQ	Soda / Modified Alkali	Soda / Modified Alkali
Recovery Challenges	Low	Low	Moderate	High	Very High

The relative magnitude of silica content across wood and selected non-wood fibers is shown in Figure 3.



*Fig. 3. Comparative silica content of wood and non-wood fibers*

### 5.3 PULPING AND PROCESSING IMPLICATIONS

The morphological and chemical characteristics described above have direct implications for mill design and operation. Bagasse and cereal straws are most commonly pulped using soda or soda–anthraquinone (AQ) processes rather than conventional kraft pulping. Soda–AQ systems improve delignification selectivity and carbohydrate preservation in non-wood pulps, thereby enhancing yield and strength development [14].

Higher chemical charges are often required in straw pulping to achieve target kappa numbers, particularly in the presence of elevated silica and extractives. Chemical recovery systems must therefore be adapted to manage increased inorganic loading and scaling tendencies. Mechanical depithing of bagasse and removal of silica-rich fractions in straw prior to pulping are common preprocessing steps designed to improve pulp uniformity and reduce stress on recovery systems [5,14].

Refining requirements also differ from wood-based pulps. Owing to shorter fiber length and thinner cell walls, non-wood fibers may respond rapidly to refining; however, excessive mechanical treatment can damage fiber structure and adversely affect drainage efficiency on the paper machine [4]. Careful control of refining energy input, freeness targets, and blending ratios is therefore essential to balance bonding development and runnability.

Extensive technical literature demonstrates that acceptable and commercially competitive paper grades can be produced from non-wood fibers when process parameters are appropriately optimized [4,5,14]. Writing and printing papers, newsprint, and selected packaging grades have been successfully manufactured using bagasse- and straw-based pulps, provided that furnish design accounts for strength reinforcement and silica management constraints.

Accordingly, the technical challenges associated with non-wood fibers are primarily operational rather than fundamental. With adapted pulping chemistry, effective recovery system management, and optimized furnish design, non-wood fibers can function as viable components within integrated pulp and paper operations.

## 6 ECONOMIC AND ENVIRONMENTAL DIMENSIONS OF NON-WOOD FIBER UTILIZATION

### 6.1 COST STRUCTURE AND COMPETITIVE POSITION

The economic viability of non-wood fiber in Indian papermaking is determined by the interaction of raw material procurement costs, pulping and recovery expenses, and market realizations for finished products. Industry analyses indicate that fiber cost remains the largest variable component in paper production economics, often accounting for approximately 40–60 percent of total manufacturing cost depending on grade and furnish composition [9].

Bagasse derived from integrated sugar–paper operations presents a distinct economic model. As a byproduct of sugar production, bagasse is generated at centralized industrial locations, eliminating primary field-level collection costs. In integrated complexes, internal transfer mechanisms and shared infrastructure reduce procurement uncertainty and logistics overhead. This integration partially shields mills from fluctuations in global pulp and recovered paper markets [12,9].

In contrast, wheat and rice straw procurement involves decentralized sourcing from agricultural fields. Costs include baling, aggregation, transport, storage, moisture management, and seasonal inventory carrying. These logistics introduce variability linked to distance from cultivation zones, crop yield fluctuations, and competition from alternative users such as biomass-based power plants and rural energy applications [8,7]. During periods of elevated biomass energy demand or drought-induced fodder scarcity, straw prices may rise, reducing its cost advantage relative to imported pulp.

Processing economics further differentiate non-wood fibers from wood-based systems. Elevated silica content in cereal straws increases chemical recovery complexity and maintenance intensity, potentially raising operating costs [5]. In addition, higher alkali consumption and yield variations influence chemical cost per tonne of pulp. However, where agro-residues are locally available at competitive prices, lower raw material acquisition costs may partially offset higher processing expenditures. Economic feasibility is therefore location-specific and dependent on integration level, production scale, and recovery system design.

### 6.2 ENVIRONMENTAL TRADE-OFFS AND RESOURCE EFFICIENCY

Environmental considerations provide a strong policy rationale for non-wood fiber utilization. Large-scale residue burning in northern India has been identified as a significant contributor to seasonal particulate pollution and greenhouse gas emissions, as documented in both regulatory assessments and peer-reviewed environmental studies [13,16]. Diversion of wheat and rice straw from open-field burning to industrial applications such as pulp production offers potential air quality benefits and supports broader environmental management objectives.

Bagasse utilization similarly represents a value-added resource pathway. Instead of being directed exclusively to combustion, bagasse can be converted into paper products with extended material life cycles prior to energy recovery. From a resource efficiency perspective,

cascading use of biomass into higher-value industrial applications before final energy extraction aligns with principles of circular resource management and improved biomass utilization efficiency [7].

However, environmental performance must be evaluated holistically. Straw pulping introduces chemical recovery challenges that may increase chemical consumption and energy intensity relative to conventional wood-based kraft operations [5]. Transportation of low bulk-density residues over long distances may also reduce net environmental benefit if logistics systems are inefficient. Consequently, lifecycle assessment (LCA) frameworks are necessary to evaluate overall environmental performance, balancing residue diversion benefits against process energy use, emissions, and chemical inputs.

Overall, non-wood fiber utilization presents both environmental opportunities and operational trade-offs. Its sustainability advantages are maximized when mills are geographically proximate to residue sources, operate efficient chemical recovery systems, and integrate residue management within broader regional biomass strategies.

## **7 STRUCTURAL CONSTRAINTS LIMITING EXPANDED UTILIZATION**

The limited share of agro-residues in India's overall fiber mix is not primarily attributable to resource scarcity, but to structural constraints embedded in supply chains, processing systems, and competing market uses. These constraints operate simultaneously and collectively restrict the scalable substitution of wood or recovered fiber.

### **7.1 SEASONALITY AND STORAGE LIMITATIONS**

Unlike recovered paper, which enters the supply chain continuously throughout the year, agricultural residues are generated within concentrated post-harvest windows. Wheat harvesting in northern India typically occurs during April and May, while rice harvesting is concentrated in October and November [6]. Sugarcane crushing seasons extend over six to eight months depending on region, but bagasse generation still follows seasonal peaks aligned with milling cycles [3].

This temporal concentration creates inventory management challenges. Mills relying heavily on straw or bagasse must either invest in substantial storage capacity to maintain year-round production or accept variable utilization rates aligned with feedstock availability. Large-scale covered storage infrastructure is capital intensive and requires fire protection systems, moisture control, and specialized material handling systems.

Residue storage also presents technical challenges. Straw and bagasse exhibit relatively low bulk density and variable moisture content, increasing space requirements and the risk of biological degradation. Prolonged storage may lead to fiber deterioration, microbial growth, and dry matter loss, affecting pulping performance and yield [5]. These factors increase working capital requirements and introduce supply risk that is less pronounced in plantation wood or recovered paper systems.

### **7.2 SILICA AND CHEMICAL RECOVERY CONSTRAINTS**

Among technical limitations, silica content in cereal straws represents the most significant barrier to expanded utilization. Rice straw may contain silica levels exceeding 10 percent, while wheat straw contains moderate but still significant inorganic fractions compared to wood [5]. During chemical pulping, silica dissolves into black liquor but does not participate in combustion or chemical regeneration within the alkali recovery cycle.

In recovery boilers and evaporators, silica can precipitate and deposit as hard scale on heat exchange surfaces, reducing thermal efficiency and increasing maintenance frequency [5,14]. Accumulation of silica also complicates causticizing operations and can limit the maximum proportion of straw that can be processed in conventional recovery systems.

To manage silica, mills may adopt mechanical depithing or pre-extraction processes to remove silica-rich fractions of straw prior to pulping [5]. Alternatively, partial bleed-off of recovery liquor can be used to prevent excessive silica buildup, but this increases chemical makeup requirements and operating costs [14]. Both strategies reduce the economic attractiveness of cereal straw relative to wood or bagasse.

### **7.3 FEEDSTOCK VARIABILITY AND PROCESS STABILITY**

Agricultural residues exhibit greater variability in physical and chemical properties than plantation-grown wood. Straw characteristics depend on crop variety, soil conditions, fertilizer application, harvest timing, and storage practices [6]. Contamination with soil, dust, and foreign matter during baling and transport further increases heterogeneity.

Such variability directly affects pulping behavior, alkali demand, fiber strength development, and drainage performance. Mills must therefore implement rigorous incoming material inspection, segregation, and blending protocols to maintain furnish consistency. Refining intensity, chemical charge, and wet-end chemistry often require continuous adjustment when residue quality fluctuates [4].

Increased process variability can reduce operational stability and increase rejection rates if quality control systems are inadequate. Consequently, mills processing agro-residues typically require more advanced raw material management systems compared to conventional wood-based operations.

#### **7.4 COMPETITION FROM ALTERNATIVE APPLICATIONS**

Agricultural residues are not exclusively available to the pulp and paper sector. Straw is widely used as livestock fodder, particularly during periods of limited green fodder availability. It is also used in rural households as fuel and increasingly as feedstock for biomass-based power generation and industrial boilers [7]. Rice straw may be incorporated into soil as organic matter to maintain soil fertility.

Bagasse has an established role in cogeneration within sugar mills, where it provides steam and electricity and may generate surplus power for grid sale [8]. The opportunity cost of diverting bagasse from energy generation to pulp production depends on prevailing electricity tariffs, energy demand, and policy incentives for renewable power.

Paper mills must therefore compete on price with these alternative applications. During periods of high biomass energy demand or elevated fodder prices, residue costs may increase, potentially eroding the economic viability of non-wood pulping relative to imported wood pulp or domestic recovered fiber [9]. This competitive landscape introduces price volatility and supply uncertainty that further constrain large-scale substitution.

### **8 POLICY FRAMEWORKS AND PATHWAYS FOR EXPANDED UTILIZATION**

Expansion of non-wood fiber utilization in India requires coordinated action across policy, infrastructure, and technology domains. Although technical feasibility has been demonstrated, large-scale adoption remains constrained by structural and economic barriers discussed earlier. Addressing these constraints requires integrated policy support alongside targeted industrial investment.

#### **8.1 POLICY INSTRUMENTS AND REGULATORY CONTEXT**

The Government of India has introduced several policy initiatives relevant to agricultural residue management. The Biomass Power and Cogeneration Programme under the Ministry of New and Renewable Energy (MNRE) provides financial incentives for biomass-based electricity generation, thereby formalizing agricultural residues as commercially valuable energy feedstocks [8]. While this strengthens the biomass market, it also intensifies competition between energy and material uses.

Air quality policies aimed at reducing stubble burning in northern India, including national action plans and state-level implementation frameworks, have direct implications for straw availability [14]. Regulatory measures and financial support mechanisms encourage farmers to adopt residue management practices such as baling, in-situ incorporation, or sale to industrial users [16]. Subsidies for straw management machinery and incentives for ex-situ utilization reduce collection costs and improve the economic feasibility of organized residue supply chains.

Although these initiatives are not designed specifically for the pulp and paper industry, they create enabling conditions for greater straw mobilization. Alignment of industrial procurement strategies with residue management policies can enhance supply reliability while reducing environmental externalities.

#### **8.2 SUPPLY CHAIN AND INFRASTRUCTURE DEVELOPMENT**

Beyond policy frameworks, physical infrastructure is essential for expanding agro-residue utilization. Efficient baling, aggregation, and transport systems must be developed in major cereal-growing regions to ensure consistent feedstock flow. Without organized logistics networks, theoretical surplus biomass cannot be translated into industrial-scale raw material supply [6].

Storage infrastructure represents a critical bottleneck. Given the seasonal concentration of residue generation, mills require covered storage facilities equipped with fire protection and moisture control systems to maintain fiber quality over extended periods. Investment in preprocessing infrastructure, including depithing and cleaning systems, can improve raw material uniformity and reduce silica-related operational stress [5].

Regional biomass aggregation centers may offer economies of scale by serving multiple end-use industries, including pulp and paper, biomass power, and bioenergy facilities. Public-private partnership models could distribute capital risk and facilitate coordinated residue mobilization across agricultural clusters [9].

### **8.3 TECHNOLOGY OPTIMIZATION AND INDUSTRIAL UPGRADING**

Technological adaptation is central to expanding non-wood fiber integration. While soda and soda–anthraquinone pulping of bagasse and straw are commercially established [14], further optimization in chemical recovery, silica management, and yield enhancement is necessary to improve cost competitiveness.

Advanced approaches discussed in technical literature include improved alkali recovery strategies for high-silica liquors, modified cooking regimes to enhance carbohydrate preservation, and process intensification through oxygen delignification stages adapted for non-wood pulps [4,5]. Enzyme-assisted pretreatment has also been explored to reduce chemical consumption and improve fiber bonding efficiency.

However, laboratory- and pilot-scale success does not automatically translate into commercial adoption. Industrial deployment requires capital investment, process stability validation, and risk mitigation mechanisms. Demonstration-scale facilities and collaborative research between mills and technical institutions can accelerate technology transfer and reduce perceived investment risk.

Strategically, expansion of non-wood fiber utilization will depend not only on policy incentives but also on the willingness of mills to invest in recovery system upgrades, furnish optimization, and integrated supply chain management.

## **9 CONCLUSION**

India possesses one of the largest agricultural residue bases in the world, yet agro-residues account for only approximately 6 to 9 percent of total fiber input in the national paper industry [1]. This limited contribution is not due to resource scarcity but to structural constraints embedded in supply chains, pulping technology, chemical recovery systems, and competing end uses. Seasonal availability, silica-related recovery challenges in cereal straws, feedstock variability, and price competition from energy and fodder applications collectively restrict large-scale substitution.

At the same time, India's paper industry is projected to continue expanding in response to rising domestic demand [2]. Wood fiber availability is unlikely to increase proportionately due to land-use limitations and regulatory constraints. Recovered paper will remain the dominant furnish, but it remains exposed to global trade volatility and supply chain disruptions. In this context, non-wood fiber represents a strategically important third component within India's broader fiber security framework.

Bagasse utilization has demonstrated commercial viability in integrated sugar–paper operations, where captive supply and adapted pulping systems support stable production. Wheat straw has proven technically workable in northern mills equipped to manage silica and logistics challenges. Bamboo continues to play a regionally significant role where forest resources permit. These examples indicate that non-wood fibers are not experimental alternatives but operationally validated raw materials under defined industrial configurations.

However, expansion beyond the current 6 to 9 percent share requires coordinated action. Policy measures supporting organized residue collection, infrastructure investment in storage and preprocessing, and technological optimization of chemical recovery systems are essential. Equally important are pricing mechanisms that maintain competitiveness relative to imported wood pulp and recovered fiber.

The fiber deficit facing India's paper industry is structural and long-term. No single raw material pathway can resolve it independently. Non-wood fiber will not replace recovered paper nor eliminate reliance on wood pulp, but it can contribute more substantially than its present share if structural barriers are systematically addressed. Realizing this potential depends on strategic investment decisions by industry and sustained policy alignment capable of converting theoretical biomass surplus into reliable industrial feedstock.

### **ABBREVIATIONS**

- CAGR – Compound Annual Growth Rate
- CEPI – Confederation of European Paper Industries
- CPPRI – Central Pulp and Paper Research Institute
- FAO – Food and Agriculture Organization of the United Nations
- IPMA – Indian Paper Manufacturers Association
- MNRE – Ministry of New and Renewable Energy
- TPA – Tonnes per annum
- TNPL – Tamil Nadu Newsprint and Papers Limited

## DECLARATIONS

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